

# ANNEX C

## Methodology for Estimating Carbon Stored in Products from Non-Energy Uses of Fossil Fuels

Carbon storage associated with the non-energy use of fossil fuels was calculated by multiplying each fuel's potential emissions (i.e., each fuel's total carbon content) by a fuel-specific storage factor. This Annex explains the methods and data sources employed in developing the storage factors for asphalt and road oil, lubricants, petrochemical feedstocks, liquefied petroleum gases (LPG), pentanes plus, and natural gas used for chemical manufacturing plant feedstocks (i.e., not used as fuel.) The storage factors for the remaining non-energy fuel uses are based on values reported by Marland and Rotty (1984) and recommended for use by IPCC (1997).

**Table C-1: Fuel Types and Percent of Carbon Stored for Non-Energy Uses**

Fuel Type	Storage Factor (%)
Industrial Coking Coal <sup>a</sup>	75%
Natural Gas to Chemical Plants	-
Nitrogenous Fertilizers	0%
Other Uses	61%
Asphalt & Road Oil	100%
Liquefied Petroleum Gas (LPG)	61%
Lubricants	9%
Pentanes Plus	61%
Petrochemical Feedstocks	-
Naphtha (b.p.<401° F)	61%
Other Oil (b.p.>401° F)	61%
Petroleum Coke <sup>b</sup>	50%
Special Naphtha	0%
Other	-
Distillate Fuel Oil	50%
Residual Fuel	50%
Waxes	100%
Miscellaneous Products	100%

- Not applicable

<sup>a</sup> Includes processes for which specific coking coal consumption and emission factor data are not available. Consumption of coking coal for production of iron and steel is covered in the Industrial Processes chapter.

<sup>b</sup> Includes processes for which specific petroleum coke consumption and emission factor data are not available (e.g., carbon fibers and textiles, refractory, electric motor parts, brake parts, batteries). Consumption of petroleum coke for production of primary aluminum anodes, electric arc furnace anodes, titanium dioxide, and ferroalloys is covered in the Industrial Processes chapter.

The following sections describe the selected non-energy uses in greater detail, outlining the methods employed and data used in estimating each storage factor. Several of the fuel types tracked by EIA—petrochemical feedstocks, pentanes plus, LPG, and natural gas—are used in organic chemical synthesis and in other manufacturing processes. Because the methods and data used to analyze them overlap, they are handled as a group and are discussed first. Discussions of the storage factors for asphalt, road oil and lubricants follow.

## Petrochemical Feedstocks, Pentanes Plus, Liquefied Petroleum Gases, and Natural Gas

Petrochemical feedstocks, pentanes plus, liquefied petroleum gases (LPG) and natural gas<sup>1</sup> are used in the manufacture of a wide variety of man-made chemicals and products. Plastics, rubber, synthetic fibers, solvents, paints, fertilizers, pharmaceuticals, and food additives are just a few of the derivatives of these four fuel types. Chemically speaking, these fuels are diverse, ranging from simple natural gas (i.e., predominantly methane, CH<sub>4</sub>) to heavier, more complex naphthas and other oils.<sup>2</sup> The storage factor for petrochemical feedstocks, pentanes plus, LPG, and natural gas used for purposes other than fuel is estimated based on data for the year 1998, which is the latest year for which data are available from several key data sources concerning consumption for non-fuel uses.

The four fuel categories constituted approximately 238.2 Tg CO<sub>2</sub> Eq., or 57 percent, of the 416.6 Tg CO<sub>2</sub> Eq. of non-energy fuel consumption in 1998. Of this amount for the four fuels, 14.3 Tg CO<sub>2</sub> Eq. was exported, resulting in a net U.S. consumption of 223.9 Tg CO<sub>2</sub> Eq. in 1998. Of this net consumption, 136.3 Tg CO<sub>2</sub> Eq. was destined for long-term storage in products—including products subsequently combusted for waste disposal—while the remaining 87.7 Tg CO<sub>2</sub> Eq. was emitted to the atmosphere directly as CO<sub>2</sub> (e.g., through combustion of industrial byproducts) or indirectly as CO<sub>2</sub> precursors (e.g., through evaporative product use). The indirect emissions include a variety of organic gases such as volatile organic compounds (VOCs) and carbon monoxide (CO), which eventually oxidize into CO<sub>2</sub> in the atmosphere. For 1998 the storage factor for the four fuel categories was 60.9 percent; this factor was assumed to be constant over the 1990 through 2001 period. The derivation of the storage factor is described in the following sections.

### Methodology and Data Sources

An empirically determined storage factor was developed for the carbon consumed for non-energy end uses of petrochemical feedstocks, pentanes plus, LPG, and natural gas (henceforth referred to as feedstocks). The storage factor is equal to the ratio of carbon stored in the final products to total carbon content for the non-energy fossil fuel feedstocks used in industrial processes, after adjusting for net exports of feedstocks. One aggregate storage factor was calculated to represent all four fuel feedstock types. The feedstocks were grouped because of the overlap of their derivative products. Due to the many reaction pathways involved in producing petrochemical products (or wastes), it becomes extraordinarily complex to link individual products (or wastes) to their parent fuel feedstocks.

Import and export data for feedstocks were obtained from the Energy Information Administration (EIA) for the major categories of petrochemical feedstocks. EIA's *Petroleum Supply Annual* (EIA 2001c) publication tracks imports and exports of petrochemical feedstocks, including butanes, butylenes, ethane, ethylene, propane, propylene, LPG, and naphthas (i.e., most of the large volume primary chemicals produced by petroleum refineries). These imports and exports are already factored into the U.S. fuel consumption statistics. However, EIA does not track imports and exports of chemical intermediates and products produced by the chemical industry (e.g., xylenes, vinyl chloride, and polypropylene resins), which were derived from the primary chemicals produced by the refineries. These products represent very large flows of carbon derived from fossil fuels (i.e., fossil carbon), so estimates of net flows not already considered in EIA's dataset were developed for the entire time series from 1990 to 2001.

The approach to estimate imports and exports involves three steps:

- Step 1.* Identify commodities derived from petrochemical feedstocks, and calculate net import/export for each.
- Step 2.* Estimate the carbon content for each commodity.
- Step 3.* Sum the net carbon imports/exports across all commodities.

Step 1 relies heavily on information provided by the National Petrochemical and Refiners Association (NPRA) and trade statistics published by the U.S. Bureau of the Census (BoC). NPRA provided a spreadsheet of

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<sup>1</sup> Natural gas has two categories of non-energy consumption: for fertilizer and for other chemical syntheses. Only natural gas that is supplied to chemical plants for other uses is included here. Natural gas used for fertilizer is not included because it covered in the Industrial Processes chapter.

<sup>2</sup> Naphthas are compounds distilled from petroleum containing 4 to 12 carbon atoms per molecule and having a boiling point less than 401° F. Other oils are distillates containing 12 to 25 carbon atoms per molecule and having a boiling point greater than 401° F.

the ten-digit BoC Harmonized Tariff Schedule (HTS) Commodity Codes used to compile import-export data for periodic reports issued to NPRA's membership on trade issues. One of the difficulties in analyzing trade data is that a large portion of the outputs from the refining industry are fuels and fuel components, and it was difficult to segregate these from the outputs used for non-energy uses. The NPRA-supplied codes identify fuels and fuel components, thus providing a sound basis for isolating net imports/exports of petrochemical feedstocks. Although MTBE and related ether imports are included in the published NPRA data, these commodities are not included in the total net imports/exports calculated here, because it is assumed that they are fuel additives and do not contribute to domestic petrochemical feedstocks. Net exports of MTBE and related ethers *are* included in the totals, however, as these commodities are petrochemicals produced from fossil fuels for export, and deplete domestic petrochemical feedstocks. Imports and exports of commodities for which production and consumption data are provided by EIA (e.g., butane, ethylene, liquefied petroleum gases) are also not included in the totals, to avoid double counting.

The BoC trade statistics are publicly available<sup>3</sup> and cover a complete time series from 1990 to 2001. These statistics include information on imports and exports of thousands of commodities. After collecting information on annual flows of the more than 100 commodities identified by NPRA, Step 2 involves calculating the carbon content for each commodity from its chemical formula. In cases where the imports and exports were expressed in units of volume, rather than mass, they were converted to mass based on the commodities' densities.

Step 3 involves summing the net carbon imports/exports across all commodities. The results of this step are shown in Table C-2. As shown in the table, the United States has been a net exporter of chemical intermediates and products throughout the 1990 to 2001 period.

**Table C-2: Net Exports of Petrochemical Feedstocks, 1990 – 2001 (Tg CO<sub>2</sub> Eq.)**

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
<b>Net Exports</b>	8.6	10.3	8.5	9.9	10.1	12.1	12.2	16.7	14.3	13.8	13.0	6.4

For each year in the inventory, the total carbon content of non-energy uses was calculated by starting with the EIA estimate of non-energy use, and reducing it by the adjustment factor for net exports (see Table C-2) to yield net domestic fuel consumption for non-energy. The balance was apportioned to either stored carbon or emissive carbon, based on a storage factor.

The overall storage factor for the feedstocks was determined by developing a mass balance on the carbon in feedstocks, and characterizing products, uses, and environmental releases as resulting in either storage or emissions. The total carbon in the system was estimated by multiplying net domestic consumption for non-energy by the carbon content of each of the feedstocks (i.e., petrochemical feedstocks-naphtha, petrochemical feedstocks-other oils, LPG, pentanes plus, natural gas). Carbon content values for the fuel feedstocks are discussed in Annexes A and B.

Next, carbon pools and releases in a variety of products and processes were characterized. The major product categories are plastics, synthetic rubber, synthetic fibers, carbon black, industrial non-methane volatile organic compound (NMVOC) emissions, industrial toxic chemical (i.e., TRI) releases, pesticides, and organic solvents.<sup>4</sup>

The carbon in each product or waste produced was categorized as either stored or emitted. The aggregate storage factor is the carbon-weighted average of storage across fuel types. As discussed later in the section on uncertainty, data were not available for all of the non-energy end uses of fuel feedstocks, so the uses analyzed represent a sample of the total carbon consumed. The sample accounts for 200.5 Tg CO<sub>2</sub> Eq., or 90 percent, of the 223.9 Tg CO<sub>2</sub> Eq. of carbon within these fuel feedstock types that is consumed domestically for non-energy purposes. The remaining 10 percent (23.4 Tg CO<sub>2</sub> Eq.) that is "unaccounted for" is assumed to be emitted, not stored. The total amount of carbon that is stored in products, including the amount subsequently emitted as CO<sub>2</sub> as a

<sup>3</sup> See the U.S International Trade Commission (USITC) Trade Dataweb at <<http://dataweb.usitc.gov/>>.

<sup>4</sup> For the most part, the releases covered by the U.S. Toxic Release Inventory (TRI) represent air emissions or water discharges associated with production facilities. Similarly, VOC emissions are generally associated with production facilities. These emissions could have been accounted for as part of the Waste chapter, but because they are not necessarily associated with waste management, they were included here. Toxic releases are not a "product" category, but they are referred to as such for ease of discussion.

result of waste combustion, corresponds to 136.3 Tg CO<sub>2</sub> Eq. Emissions of CO<sub>2</sub> from waste combustion are accounted for separately in the Inventory and are discussed in the Waste Combustion section of the Energy chapter.

The following sections provide details on the calculation steps, assumptions, and data sources employed in estimating and classifying the carbon in each product and waste shown in Table C-2. Summing the carbon stored and dividing it by the total fuel feedstock carbon used yields the overall storage factor, as shown in the following equation:

$$\text{Overall Storage Factor} = \text{Carbon Stored} / \text{Total Carbon} = 136.3 \text{ Tg CO}_2 \text{ Eq.} / 223.9 \text{ Tg CO}_2 \text{ Eq.} = 60.9 \%$$

**Table C-3: Carbon Stored and Emitted by Products from Petrochemical Feedstocks, Pentanes Plus, LPG, and Natural Gas in 1998 (Tg CO<sub>2</sub> Eq.)**

Product/Waste Type	Carbon Stored	Carbon Emitted
Industrial Releases	0.1	8.2
TRI Releases	0.1	1.0
Industrial VOCs		4.0
Non-combustion CO	-	1.3
Refinery wastewater		0.1
Hazardous Waste Incin.	-	1.9
Energy Recovery	-	41.1
Products	136.2	15.0
Plastics	110.4	-
Synthetic Rubber	7.7	-
Synthetic Fiber	11.7	-
Carbon Black	5.9	-
Pesticides	0.4	0.2
Soaps, shampoos, detergents		4.9
Solvent VOCs	-	9.9
Unaccounted for*		23.4
<b>Total</b>	<b>136.3</b>	<b>87.7</b>

- Not applicable

\* Unaccounted for carbon was assumed to be emitted.

Note: Totals may not sum due to independent rounding.

The three categories of carbon accounted for in the table are industrial releases, energy recovery, and products. Each is discussed below.

### **Industrial Releases**

Industrial releases include toxics reported through the Toxics Release Inventory, industrial emissions of volatile organic compounds (VOCs), carbon monoxide emissions (other than those related to fuel combustion), treatment of refinery wastewater, and hazardous waste incineration.

### **TRI Releases**

Carbon is also found in toxic substances released by industrial facilities. The Toxic Release Inventory (TRI), maintained by EPA, tracks these releases by chemical and environmental release medium (i.e., land, air, or water) on a biennial basis (EPA 2000b). By examining the carbon contents and receiving media for the top 35 toxic chemicals released, which account for 90 percent of the total mass of chemicals, the quantity of carbon stored and emitted in the form of toxic releases can be estimated.

The TRI specifies releases by chemical, so carbon contents were assigned to each chemical based on molecular formula. The TRI also classifies releases by disposal location as either off-site or on-site. The on-site releases are further subdivided into air emissions, surface water discharges, underground injection, and releases to

land; the latter is further broken down to disposal in a RCRA Subtitle C (i.e., hazardous waste) landfill or to “Other On-Site Land Disposal.”<sup>5</sup> The carbon released in each disposal location is provided in Table C-4.

Each on-site classification was assigned a storage factor. A one hundred percent storage factor was applied to disposition of carbon to underground injection and to disposal to RCRA-permitted landfills, while the other disposition categories were assumed to result in an ultimate fate of emission as CO<sub>2</sub> (i.e., a storage factor of zero was applied to these categories.) The release allocation is not reported for off-site releases; therefore, the approach was to develop a carbon-weighted average storage factor for the on-site carbon and apply it to the off-site releases.

For the remaining 10 percent of the TRI releases, the weights of all chemicals were added and an average carbon content value, based upon the top 35 chemicals’ carbon contents, was applied. The storage and emission allocation for the remaining 10 percent of the TRI releases was carried out in the same fashion as for the 35 major chemicals.

**Table C-4: 1998 TRI Releases by Disposal Location (Gg CO<sub>2</sub> Eq.)**

Disposal Location	Carbon Stored	Carbon Emitted
Air Emissions	-	924.0
Surface Water Discharges	-	6.7
Underground Injection	89.4	-
RCRA Subtitle C Landfill Disposal	1.4	-
Other On-Site Land Releases	-	15.9
Off-site Releases	6.4	36.0
<b>Total</b>	<b>97.2</b>	<b>982.6</b>

- Not applicable

Note: Totals may not sum due to independent rounding.

#### *Volatile Organic Compound Emissions from Industrial Processes and Solvent Evaporation*

Data on annual non-methane volatile organic compound (NMVOC) emissions were obtained from the National Air Quality and Emissions Trends Report (EPA 2000b). The report includes information on NMVOC emissions end-use category; some of these fall into the heading of “industrial releases” in Table C-3 above, and others are related to “product use”; for ease of discussion, both are covered here. The end-use categories that represent “Industrial NMVOC Emissions” include chemical and allied products, petroleum and related industries, and other industrial processes. NMVOC emissions from solvent utilization (product use) were considered to be a result of non-energy use of petrochemical feedstocks. These categories were used to distinguish non-energy uses of the four fuel types from energy uses; other categories where VOCs could be emitted due to combustion of fossil fuels were excluded to avoid double counting.

Because solvent evaporation and industrial NMVOC emission data are provided in tons of total NMVOCs, assumptions were made concerning the average carbon content of the NMVOCs for each category of emissions. The assumptions for calculating the carbon fraction of industrial and solvent utilization emissions were made separately and differ significantly. For industrial NMVOC emissions, the carbon content of 85 percent was assumed. This value was chosen to reflect the carbon content of an average volatile organic compound based on the list of the most abundant NMVOCs provided in the Trends Report. The list contains only pure hydrocarbons, including saturated alkanes (carbon contents ranging from 80 to 85 percent based upon carbon number), alkenes (carbon contents equal 85.7 percent), and some aromatics (carbon contents approximately 90 percent, depending upon substitution).

An EPA solvent evaporation emissions dataset (EPA 2000b) was used directly to estimate the carbon content of solvent emissions. The dataset identifies solvent emissions by compound or compound category for six different solvent end-use categories: degreasing, graphic arts, dry cleaning, surface coating, other industrial processes, and non-industrial processes. The percent carbon of each compound identified in the EPA solvent evaporation emissions dataset was calculated based on the molecular formula of the individual compound (e.g., the

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<sup>5</sup> Only the top 9 chemicals had their land releases separated into RCRA Landfills and Other Land Disposal. For the remaining chemicals, it was assumed that the ratio of disposal in these two categories was equal to the carbon-weighted average of the land disposal fate of the top 9 chemicals (i.e., 8 percent attributed to RCRA Landfills and 92 percent in the “Other” category).

carbon content of methylene chloride is 14 percent; the carbon content of toluene is 91 percent). For solvent emissions that are identified in the EPA dataset only by chemical category (e.g., butanediol derivatives) a single individual compound was selected to represent each category, and the carbon content of the category was estimated based on the carbon content of the representative compound. The overall carbon content of the solvent evaporation emissions is estimated to be 56 percent.

The results of the industrial and solvent NMVOC emissions analysis are provided in Table C-5.

**Table C-5: 1998 Industrial and Solvent NMVOC Emissions**

Activity	Thousand short tons	Carbon Content	Carbon Emitted (Tg CO <sub>2</sub> Eq.)
Industrial NMVOCs <sup>a</sup>	1,417	85%	4.0
Solvent Evaporation <sup>b</sup>	4,950	56%	9.9

<sup>a</sup> Includes emissions from chemical and allied products, petroleum and related industries, and other industrial processes categories.

<sup>b</sup> Includes solvent usage and solvent evaporation emissions from degreasing, graphic arts, dry cleaning, surface coating, other industrial processes, and non-industrial processes.

#### *Non-Combustion Carbon Monoxide Emissions*

Carbon monoxide (CO) emissions data were obtained from the National Air Quality and Emissions Trends Report (EPA 2000a). There are four categories of CO emissions in EPA (2000a) that are classified as process-related emissions not related to fuel combustion. These include chemical and allied products manufacturing, metals processing, petroleum and related industries, and other industrial processes. Some of these CO emissions are accounted for in the Industrial Processes section of this report, and are therefore not accounted for in this section, including total carbon emissions from the primary aluminum, titanium dioxide, iron and steel, and ferroalloys production processes. The total carbon (CO and CO<sub>2</sub>) emissions from oil and gas production and asphalt manufacturing are also accounted for elsewhere in this Inventory. Sustainably harvested biogenic emissions (e.g., pulp and paper process emissions) are also excluded from calculation of CO emissions in this section. Those CO emissions that are not accounted for elsewhere are considered to be byproducts of non-fuel use of feedstocks and are included in the calculation of the petrochemical feedstocks storage factor. Table C-6 lists the industrial processes and CO emissions that remain after taking into account the exclusions above.

**Table C-6: Carbon Monoxide Non-Combustion Emissions (Gg)**

Source	1998
<b>Chemical and Allied Products</b>	
Organic Chemical Manufacture	83.6
Inorganic Chemical Manufacture, Other	2.7
Polymer and Resin Manufacture	4.5
Agricultural Chemical Manufacture	11.8
Paint, Varnish, Lacquer Manufacture	-
Pharmaceutical Manufacture	-
Other Chemical Manufacture	23.6
<b>Metals Processing</b>	
Nonferrous Metals Processing, Other	145.5
Metals Processing NEC	40.0
<b>Petroleum and Related Industries</b>	
Petroleum Refineries and Related Industry	300.9
<b>Other Industrial Processes</b>	
Rubber and Misc. Plastic Products	-
Mineral Products	169.1
Machinery Products	0.91
Electronic Equipment	-
Transportation Equipment	-
Misc. Industrial Processes	18.2
<b>Total</b>	<b>801.7</b>
<b>Total (Tg CO<sub>2</sub> Eq.)</b>	<b>1.3</b>

Note: Totals may not sum due to independent rounding.

### *Refinery Wastewater*

Carbon flows associated with the treatment and discharge of refinery wastewater are included in the mass balance. To develop an estimate of annual emissions associated with the wastewater, it was assumed that the average concentration of Total Organic Carbon in refinery effluents was 10.5 mg/L, based on 1992 data reported in EPA's Permit Compliance System. It was also assumed that (a) the overall treatment efficiency (excluding recycling of oil back to the refinery) was 90 percent, (b) average flow is about 1 million gallons per day (3,800 m<sup>3</sup>/day), there are 192 operating refineries in the United States, (c) the majority of organic compounds in refinery wastewater are not covered by the TRI requirements (and thus there is no significant double-counting of releases with the TRI estimate), and (d) all of the carbon in the raw wastewater is destined for emission as CO<sub>2</sub>. Based on these assumptions, annual emissions are roughly 0.1 Tg CO<sub>2</sub> Eq. Note that fugitive air emissions of methane from treatment of refinery wastewater are already accounted for in the inventory in the category of "Petroleum Systems," but other fugitive air emissions and discharges of wastewater to surface water or publicly owned treatment works are not included elsewhere in the inventory.

### *Hazardous Waste Incineration*

Hazardous wastes are defined by the EPA under the Resource Conservation and Recovery Act (RCRA).<sup>6</sup> Industrial wastes, such as rejected products, spent reagents, reaction by-products, and sludges from wastewater or air pollution control, are federally regulated as hazardous wastes if they are found to be ignitable, corrosive, reactive, or toxic according to standardized tests or studies conducted by the EPA.

Hazardous wastes must be treated prior to disposal according to the federal regulations established under the authority of RCRA. Combustion is one of the most common techniques for hazardous waste treatment, particularly for those wastes that are primarily organic in composition or contain primarily organic contaminants. Generally speaking, combustion devices fall into two categories: incinerators that burn waste solely for the purpose of waste management, and boilers and industrial furnaces (BIFs) that burn waste in part to recover energy from the waste. More than half of the hazardous waste combusted in the U.S. is burned in BIFs; these processes are included in the energy recovery calculations described above.

EPA's Office of Solid Waste requires biennial reporting of hazardous waste management activities, and these reports provide estimates of the amount of hazardous waste burned for incineration or energy recovery.

EPA stores this information in its Biennial Reporting System (BRS) database (EPA 2000a). Combusted hazardous wastes are identified based on EPA-defined management system types M041 through M049 (incineration). Combusted quantities are grouped into four representative waste form categories based on the form codes reported in the BRS: aqueous liquids, organic liquids and sludges, organic solids, and inorganic solids. To relate hazardous waste quantities to carbon emissions, "fuel equivalent" factors were derived for hazardous waste by assuming that the hazardous wastes are simple mixtures of a common fuel, water, and noncombustible ash. For liquids and sludges, crude oil is used as the fuel equivalent and coal is used to represent solids.

Fuel equivalent factors were multiplied by the tons of waste incinerated to obtain the tons of fuel equivalent. Multiplying the tons of fuel equivalent by the appropriate carbon content factors from Marland and Rotty (1984) yields tons of carbon emitted. Implied carbon content is calculated by dividing the tons of carbon emitted by the associated tons of waste incinerated.

Waste quantity data for hazardous wastes were obtained from EPA's BRS database for reporting years 1989, 1991, 1993, 1995, and 1997 (EPA 2000a). Combusted waste quantities were obtained from Form GM (Generation and Management) for wastes burned on site and Form WR (Wastes Received) for waste received from off-site for combustion. For each of the waste types, assumptions were developed on average waste composition (see Table C-7). Carbon emission factors for equivalent fuels were obtained from Marland and Rotty (1984). Regulations require incinerators to achieve at least 99.99 percent destruction of organics; this formed the basis for assuming the fraction of carbon oxidized. A least-squares linear regression from the time series 1989 through 1997 was used to estimate emissions for 1998.

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<sup>6</sup> [42 U.S.C. §6924, SDWA §3004]

**Table C-7: Assumed Composition of Combusted Hazardous Waste by Weight (Percent)**

Waste Type	Water	Noncombustibles	Fuel Equivalent
Aqueous Waste	90	5	5
Organic Liquids and Sludges	40	20	40
Organic Solids	20	40	40
Inorganic Solids	20	70	10

**Energy Recovery**

The amount of fuel feedstocks that are combusted for energy recovery was estimated from data included in EIA's Manufacturers Energy Consumption Survey (MECS) for 1998 (EIA 2001b). Fuel feedstocks may be combusted for energy recovery because the chemical reactions in which fuel feedstocks are used are not 100 percent efficient. These chemical reactions may generate unreacted raw material feedstocks or generate byproducts that have a high energy content. The chemical industry and many downstream industries are energy-intensive, and therefore unreacted feedstocks or byproducts of production may be combusted for energy recovery in industrial boilers. Also, hazardous waste regulations provide a strong incentive—and in some cases require—burning of organic wastes generated from chemical production processes. Combustion of hazardous waste without energy recovery is referred to as “incineration,” and is discussed separately in this Annex.

MECS data include data on the consumption for energy recovery of “other” fuels in the petroleum and coal products, chemicals, primary metals, nonmetallic minerals, and other manufacturing sectors. These “other” fuels include refinery still gas; waste gas; waste oils, tars, and related materials; petroleum coke, coke oven and blast furnace gases; and other uncharacterized fuels. Fuel use of petroleum coke is included separately in the fuel use data provided annually by EIA, and energy recovery of coke oven gas and blast furnace gas (i.e., byproducts of the iron and steel production process) is addressed in the Iron and Steel production section in the Industrial Processes chapter. Consumption of refinery still gas and “other” fuels in the refinery sector is also included separately in the fuel use data from EIA. Therefore these categories of “other” fuels are addressed elsewhere in the inventory and not considered as part of the petrochemical feedstocks energy recovery discussion. The remaining categories of fuels included in the 1998 MECS data (Table C-8) including waste gas; waste oils, tars, and related materials; and other uncharacterized fuels are assumed to be petrochemical feedstocks burned for energy recovery. The conversion factors listed in Annex A were used to convert the Btu values for each fuel feedstock to Tg CO<sub>2</sub>. Petrochemical feedstocks combusted for energy recovery corresponded to 41.1 Tg CO<sub>2</sub> Eq. in 1998.

**Table C-8: Summary of 1998 MECS Data for Other Fuels used in Manufacturing/Energy Recovery (Trillion Btu)**

Subsector and Industry	NAICS Code	Waste Gas <sup>b</sup>	Waste Oils/Tars <sup>c</sup>	Refinery Still Gas <sup>d</sup>	Net Steam <sup>e</sup>	Other Fuels <sup>f,g</sup>
Printing and Related Support	323	0	1	0	0	0
Petroleum and Coal Products	324	0	1	1399	0	324 <sup>a</sup>
Chemicals	325	416	16	0	194	118 <sup>a</sup>
Plastics and Rubber Products	326	0	0	0	0	0
Nonmetallic Mineral Products	327	2	9	0	0	14
Primary Metals	331	2	2	0	0	22
Fabricated Metal Products	332	1	0	0	0	0
Machinery	333	0	1	0	0	0
Computer and Electronic Products	334	0	0	0	0	0
Electrical Equipment, Appliances, Components	335	1	1	0	0	0
Transportation Equipment	336	1	2	0	0	0
<b>Total</b>		<b>423</b>	<b>33</b>	<b>1399</b>	<b>194</b>	<b>478</b>
Carbon Content (Tg/QBTU)		18.1	20.6	17.5	0	19.4
Fraction Oxidized		99%	99%	99%	0%	99%
<b>Total Carbon (Tg)</b>		<b>7.6</b>	<b>0.7</b>	<b>24.2</b>	<b>0.0</b>	<b>9.2</b>
<b>Total Carbon (Non-Refining)</b>		<b>7.6</b>	<b>0.7</b>	<b>0.0</b>	<b>0.0</b>	<b>3.0</b>

<sup>a</sup> EIA personal communication, 2001.

<sup>b</sup> C content assumed to be naphtha <401F.

<sup>c</sup> C content assumed to be asphalt and road oil.

<sup>d</sup> Refinery “other” fuel consumption is reported elsewhere in the inventory and is excluded from the total carbon. The total non-refining total carbon excludes all “other” fuel consumption under NAICS Code 325 (Petroleum and Coal Products).

<sup>e</sup> Net steam is reported elsewhere in the inventory and is excluded from the total carbon content estimate.

<sup>f</sup> Assumed to be petrochemical feedstocks.

<sup>g</sup> Includes net steam, except for NAICS Code 325 (Chemicals). Net steam for other sectors assumed to be negligible.



Note: Totals may not sum due to independent rounding.

## Products

More carbon is found in products than in industrial releases or energy recovery. The principal types of products are plastics; synthetic rubber; synthetic fiber; carbon black; pesticides; soaps, detergents, and cleansers; and solvents. Solvent evaporation was discussed previously along with industrial releases of NMVOCs; the other product types are discussed below.

## Plastics

Data on annual production of plastics were taken from the American Plastics Council, as published in *Chemical & Engineering News* and through direct communication with the APC (APC 2000, Eldredge-Roebuck 2000). These data were organized by year and resin type (see Table C-9). A carbon content was assigned for each resin. These contents were based on molecular formulas and are listed in Table C-10 and Table C-11. In cases where the resin type is generic, referring to a group of chemicals and not a single polymer (e.g., phenolic resins, other styrenic resins), a representative compound was chosen. For engineering resins and other resins, a weighted carbon content of 65 percent was assumed (i.e., it was assumed that these resins had the same content as those for which a representative compound could be assigned).

There were no emissive uses of plastics identified, so 100 percent of the carbon was considered stored in products. However, an estimate of emissions related to the combustion of these plastics in the municipal solid waste stream can be found in the Waste Combustion section of the Energy chapter.

**Table C-9: 1998 Plastic Resin Production (Tg dry weight) and Carbon Stored (Tg CO<sub>2</sub> Eq.)**

Resin Type	1998 Production <sup>a</sup>	Carbon Stored
Epoxy	0.29	0.8
Polyester (Unsaturated)	0.78	1.8
Urea	1.17	1.5
Melamine	0.13	0.1
Phenolic	1.79	5.0
Low-Density Polyethylene (LDPE)	3.44	10.8
Linear Low-Density Polyethylene (LLDPE)	3.28	10.3
High Density Polyethylene (HDPE)	5.86	18.4
Polypropylene (PP)	6.27	19.7
Acrylonitrile-butadiene-styrene (ABS)	0.65	2.0
Styrene-acrylonitrile (SAN)	0.06	0.2
Other Styrenics	0.75	2.5
Polystyrene (PS)	2.83	9.6
Nylon	0.58	1.4
Polyvinyl chloride (PVC) <sup>b</sup>	6.58	9.3
Thermoplastic Polyester	2.01	4.6
Engineering Resins	1.25	3.0
All Other	3.88	9.4
<b>Total</b>	<b>41.59</b>	<b>110.4</b>

<sup>a</sup> Includes production from Canada for ABS, SAN, PVC, PP, Phenolic, Urea, Melamine, and Thermoplastic Polyester

<sup>b</sup> Includes copolymers

Note: Totals may not sum due to independent rounding.

**Table C-10: Assigned Carbon Contents of Plastic Resins (by weight)**

Resin Type	Carbon Content	Source of Carbon Content Assumption
Epoxy	76%	Typical epoxy resin made from epichlorhydrin and bisphenol A
Polyester (Unsaturated)	63%	Poly (ethylene terephthalate) (PET)
Urea	34%	50% carbamal, 50% N-(hydroxymethyl) urea *
Melamine	29%	Trimethylol melamine *
Phenolic	77%	Phenol
Low-Density Polyethylene (LDPE)	86%	Polyethylene

Linear Low-Density Polyethylene (LLDPE)	86%	Polyethylene
High Density Polyethylene (HDPE)	86%	Polyethylene
Polypropylene (PP)	86%	Polypropylene
Acrylonitrile-Butadiene-Styrene (ABS)	85%	50% styrene, 25% acrylonitrile, 25% butadiene
Styrene-Acrylonitrile (SAN)	80%	50% styrene, 50% acrylonitrile
Other Styrenics	92%	Polystyrene
Polystyrene (PS)	92%	Polystyrene
Nylon	65%	Average of nylon resins (see Table C-11)
Polyvinyl Chloride (PVC)	38%	Polyvinyl chloride
Thermoplastic Polyester	63%	Polyethylene terephthalate
Engineering Resins	66%	Weighted average of other resin production
All Other	66%	Weighted average of other resin production

\*Does not include alcoholic hydrogens.

**Table C-11: Major Nylon Resins and their Carbon Contents (by weight)**

Resin	Carbon Content
Nylon 6	64%
Nylon 6,6	64%
Nylon 4	52%
Nylon 6,10	68%
Nylon 6,11	69%
Nylon 6,12	70%
Nylon 11	72%

### *Synthetic Rubber*

Data on annual consumption of synthetic rubber were obtained from the International Institute of Synthetic Rubber Producers (IISRP) press release “Synthetic Rubber Use Growth to Continue Through 2004, Says IISRP and RMA” (IISRP 2000). Due to the fact that production data for synthetic rubber were unavailable, consumption was assumed to equal production. These data were organized by year and elastomer type. A carbon content was assigned for each elastomer type. These contents, based on stoichiometry, are listed in Table C-12. For the “Others” category, a weighted carbon content was calculated from total 1998 consumption data.

There were no emissive uses of rubber identified, so 100 percent of the carbon was assumed stored. However, emissions related to the combustion of scrap tires and rubber consumer goods can be found in the Waste Combustion section of the Energy chapter.

**Table C-12: 1998 Rubber Consumption, Carbon Content, and Carbon Stored**

Elastomer Type	1998 Consumption (Thousand Metric Tons) *	Carbon Content	Carbon Stored (Tg CO <sub>2</sub> Eq.)
SBR Solid	908	91%	3.0
Polybutadiene	561	89%	1.8
Ethylene Propylene	320	86%	1.0
Polychloroprene	69	59%	0.1
NBR Solid	87	77%	0.2
Polyisoprene	78	88%	0.3
Others	369	88%	1.2
<b>Total</b>	<b>2,392</b>	<b>-</b>	<b>7.7</b>

\* Includes consumption in Canada.

- Not applicable

Note: Totals may not sum due to independent rounding.

### *Synthetic Fibers*

Annual synthetic fiber production data were obtained from the Fiber Economics Bureau, as published in Chemical & Engineering News and exhibited on the FiberSource website (FEB 2000). These data are organized by year and fiber type. For each fiber, a carbon content was assigned based on stoichiometry (see Table C-13). For polyester, the carbon content for poly(ethylene terephthalate) (PET) was used as a representative compound. For nylon, the average carbon content of nylon 6 and nylon 6,6 was used, since these are the most widely produced

nylon fibers. Cellulosic fibers, such as acetate and rayon, have been omitted from the synthetic fibers' carbon accounting because much of their carbon is of biogenic origin. These fibers account for only 4 percent of overall fiber production by weight.

There were no emissive uses of fibers identified, so 100 percent of the carbon was considered stored. Note that emissions related to the combustion of textiles in municipal solid waste is accounted for under the Waste Combustion section of the Energy chapter.

**Table C-13: 1998 Fiber Production, Carbon Content, and Carbon Stored**

Fiber Type	Production (Tg)	Carbon Content	Carbon Stored (Tg CO <sub>2</sub> Eq.)
Polyester	1.8	63%	4.1
Nylon	1.3	64%	3.0
Olefin	1.3	86%	4.1
Acrylic	0.2	68%	0.5
<b>Total</b>	<b>4.6</b>	<b>-</b>	<b>11.7</b>

- Not applicable

Note: Totals may not sum due to independent rounding

#### *Carbon Black*

Carbon black is a finely divided solid form of carbon produced from the partial oxidation of heavy oil fractions.<sup>7</sup> It is used primarily in manufacture of tire treads and other abrasion resistant rubber products, but can also be used in pigments for paints and inks. In 1998, carbon black ranked 35<sup>th</sup> in chemical production in the United States with 1,610,280 metric tons produced (CMA 1999). Since carbon black is essentially pure carbon, its carbon content was assumed to be 100 percent. Also, since it is used in solid products and resists degradation, it was considered 100 percent stored. For 1998, carbon stored as a result of carbon black production was estimated to be 5.9 Tg CO<sub>2</sub> Eq.

#### *Pesticides*

Pesticide consumption data were obtained from the *1996/1997 Pesticides Industry Sales and Usage* (EPA 1999) report. The most recent data available were for 1995 through 1997, so it was assumed that 1998 consumption was equal to that of these years. Although some production data were available, consumption data were used because these data provided information on active ingredients. Active ingredient compound names and consumption weights were available for the top 25 agriculturally-used pesticides and top 9 pesticides used in the home and garden and the industry/commercial/government categories. The report provides a range of consumption for each active ingredient; the midpoint was used to represent actual consumption. Each of these compounds was assigned a carbon content value based on molecular formula. If the compound contained aromatic rings substituted with chlorine or other halogens, then the compound was considered persistent and the carbon in the compound was assumed to be stored. All other pesticides were assumed to release their carbon to the atmosphere. Nearly one-third of total pesticide active ingredient consumption was not specified by chemical type in the *Sales and Usage* report (EPA 1999). This unspecified portion of the active ingredient consumption was treated as a single chemical and assigned a carbon content and a storage factor based on the weighted average of the known chemicals' values.

**Table C-14: Active Ingredient Consumption in Pesticides (Million lbs.) and Carbon Emitted and Stored (Tg CO<sub>2</sub> Eq.)**

Pesticide Use	Active Ingredient	Carbon Emitted	Carbon Stored
<b>Agricultural Uses</b> <sup>a</sup>	<b>551.0</b>	<b>0.1</b>	<b>0.2</b>
<b>Non-Agricultural Uses</b> <sup>b</sup>	<b>84.5</b>	<b>+</b>	<b>+</b>
Home & Garden	34.0	+	+
Industry/Gov't/Commercial	50.5	+	+
<b>Other</b>	<b>334.5</b>	<b>0.1</b>	<b>0.1</b>
<b>Total</b>	<b>970.0</b>	<b>0.2</b>	<b>0.4</b>

+ Less than 0.05 Tg CO<sub>2</sub> Eq.

<sup>a</sup>1997 estimate (EPA 1999).

<sup>b</sup> Approximate quantities, 1995/1996 estimates (EPA 1999).

<sup>7</sup> Carbon black can also be produced from the cracking of natural gas, but this method is uncommon.

Note: Totals may not sum due to independent rounding.

### *Soaps, Shampoos, and Detergents*

Cleansers – soaps, shampoos, and detergents—are among the major consumer products that may contain fossil carbon. All of the carbon in cleansers was assumed to be fossil derived, and, as cleansers eventually biodegrade, all of the carbon was assumed to be emitted. The first step in estimating carbon flows was to characterize the “ingredients” in a representative sampling of cleansers. For this analysis, cleansers were limited to the following personal household cleaning products: bar soap, shampoo, laundry detergent (liquid and granular), dishwasher detergent, and dishwashing liquid. Data on the annual consumption of household personal cleansers were obtained from the U.S. Census Bureau 1997 Economic Census. The year 1997 was taken to be a representative year, as it is the most recent year for which comprehensive data were available.

Chemical formulae were used to determine carbon contents (as percentages) of the ingredients in the cleansers. Each product’s overall carbon content was then derived from the composition and contents of its ingredients. From these values the mean carbon content for cleansers was calculated to be 21.9 percent.

The Census Bureau presents consumption data in terms of quantity (in units of million gallons or million pounds) and/or terms of value (thousands of dollars) for eight specific categories, such as “household liquid laundry detergents, heavy duty” and “household dry alkaline automatic dishwashing detergents.” Additionally the report provides dollar values for the total consumption of “soaps, detergents, etc.—dry” and “soaps, detergents, etc.—liquid.” The categories for which both quantity and value data are available is a subset of total production. Those categories that presented both quantity and value data were used to derive pounds per dollar and gallons per dollar conversion rates, and they were extrapolated (based on the Census Bureau estimate of total value) to estimate the total quantity of dry and liquid<sup>8</sup> cleanser categories, respectively.

Next, the total tonnage of cleansers was calculated (wet and dry combined). Multiplying the mean carbon content (21.9 percent) by this value yielded an estimate of the 1998 amount of carbon in cleansers of 4.9 Tg CO<sub>2</sub> Eq.

### **Uncertainty**

There are several cross-cutting sources of uncertainty that pervade the characterization of a storage factor for feedstocks. The aggregate storage factor for petrochemical feedstocks, pentanes plus, liquefied petroleum gases, and natural gas is based on only a partial sampling of the releases and products derived from these fossil fuel feedstocks and imports and exports of petrochemical feedstocks. Including consideration of petrochemical feedstocks that are exported and feedstocks that are burned for energy recovery, approximately 90 percent of the carbon consumed across these fuel types for non-energy uses is accounted for. The remaining “unaccounted-for” carbon could have a variety of fates. For the purposes of this inventory, all of the unaccounted for carbon was assumed to be emitted, and using this assumption the overall storage factor is 60.9 percent. If the assumption had been made that the products which contained the unaccounted for carbon would store and emit carbon in the same ratio as the investigated releases and products, the overall storage factor would have been 67.9 percent, rather than 60.9 percent.

With respect to the “unaccounted for” carbon, there are uncertainties associated with the EIA data—which provide the initial carbon input—and the data for net imports and exports of feedstocks that could affect the calculation of the storage factor. To a lesser extent, there are uncertainties associated with the simplifying assumptions made for each end use category carbon estimate. Generally, the estimate for a product is subject to one or both of the following uncertainties:

- The value used for estimating the carbon content has been assumed or assigned based upon a representative compound.
- The split between carbon storage and emission has been assumed based on an examination of the environmental fate of the products in each end use category.
- Environmental fates leading to emissions are assumed to operate rapidly, i.e., emissions are assumed to occur within one year of when the fossil carbon enters the non-energy mass balance. Some of the pathways that lead to emissions as CO<sub>2</sub> may take actually place on a time-scale of several years or decades. By

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<sup>8</sup> A density of 1.05 g/mL—slightly denser than water—was assumed for liquid cleansers.

attributing the emissions to the year in which the carbon enters the mass balance (i.e., the year in which it leaves refineries as a non-energy fuel use and thus starts being tracked by EIA), this approach has the effect of “front-end loading” the emission profile.

Another cross-cutting source of uncertainty is that the estimate of the balance between storage and emissions is based on data for only for a single year, 1998. This specific year may not be representative of storage for the entire inventory period.

Sources of uncertainty associated with specific elements of the analysis are discussed below.

### ***Imports/Exports***

Import and export data for petrochemical feedstocks were obtained from EIA and the National Petroleum Refiners Association for the major categories of petrochemical feedstocks (EIA 2001a, NPRA 2001). The list of commodities for which imports and exports were analyzed is not comprehensive in tracking fossil fuel-derived feedstocks. In particular, the commodity codes used for the analysis do not track many secondary products or even some primary fossil fuel-derived products (e.g., the NPRA list of commodity codes includes polyethylene and polypropylene but not polystyrene, which is also a fossil fuel-derived commodity). Based on a limited screening analysis of additional relevant commodity codes, it appears that the current approach is likely to underestimate net exports of carbon. All unaccounted for carbon is currently assumed to be emitted. If net exports are higher than calculated here, the “missing” carbon would be lower, and thus emissions would be correspondingly lower.

### ***Oxidation Factors***

Oxidation factors have been applied to non-energy uses of petrochemical feedstocks in the same manner as for energy uses. However, this “oxidation factor” may be inherent in the storage factor applied when calculating emissions from non-energy consumption, which would result in a double-counting of the unoxidized carbon. Oxidation factors are small corrections, on the order of 1 percent, and therefore application of oxidation factors to non-energy uses may result in a slight underestimation of carbon emissions from non-energy uses.

### ***TRI***

The major uncertainty in using the TRI data are the possibility of double counting of emissions that are already accounted for in the NMVOC data (see above) and in the storage and emission assumptions used. The approach for predicting environmental fate simplifies some complex processes, and the balance between storage and emissions is very sensitive to the assumptions on fate. Extrapolating from known to unknown characteristics also introduces uncertainty. The two extrapolations with the greatest uncertainty are: 1) that the release media and fate of the off-site releases were assumed to be the same as for on-site releases, and 2) that the carbon content of the least frequent 10 percent of TRI releases was assumed to be the same as for the chemicals comprising 90 percent of the releases. However, the contribution of these chemicals to the overall estimate is small. The off-site releases only account for 3 percent of the total releases, by weight, and, by definition, the less frequent compounds only account for 10 percent of the total releases.

### ***NMVOCs (Solvent Evaporation and Industry)***

The principal sources of uncertainty in estimating CO<sub>2</sub> emissions from solvent evaporation and industry are in the estimates of total NMVOC emissions and in the application of factors for the carbon content of these emissions. Solvent evaporation and industrial NMVOC emissions reported by EPA are based on a number of data sources and emission factors, and may underestimate or overestimate emissions. The carbon content for solvent evaporation emissions is calculated directly from the specific solvent compounds identified by EPA as being emitted, and is thought to have relatively low uncertainty. The carbon content for industrial emissions has more uncertainty, however, as it is calculated from the average carbon content of an average volatile organic compound based on the list of the most abundant measured NMVOCs provided in EPA (2000b).

### ***Hazardous Waste***

Uncertainty in the hazardous waste combustion analysis is introduced by the assumptions about the composition of combusted hazardous wastes, including the characterization that hazardous wastes are similar to mixtures of water, noncombustibles, and fuel equivalent materials. Another limitation is the assumption that all of the carbon that enters hazardous waste combustion is emitted—some small fraction is likely to be sequestered in combustion ash—but given that the destruction and removal efficiency for hazardous organics is required to meet or exceed 99.99 percent, this is a very minor source of uncertainty. Carbon emission estimates from hazardous waste should be considered central value estimates that are likely to be accurate to within  $\pm 50$  percent.

### ***Energy Recovery***

The amount of feedstocks combusted for energy recovery was estimated from data included in the Manufacturers Energy Consumption Survey (MECS) for 1998 (EIA 2001b). MECS is a comprehensive survey intended to represent U.S. industry as a whole, but because EIA does not receive data from all manufacturers (i.e., it is a sample rather than a census), EIA must extrapolate from the sample. Also, the “other” fuels are identified in the 1998 MECS data in broad categories, including refinery still gas; waste gas; waste oils, tars, and related materials; petroleum coke, coke oven and blast furnace gases; and other uncharacterized fuels. Moreover, the industries using these “other” fuels are also identified only in broad categories, including the petroleum and coal products, chemicals, primary metals, nonmetallic minerals, and other manufacturing sectors. The “other” fuel consumption data are reported in BTUs (energy units) and there is uncertainty concerning the selection of a specific conversion factor for each broad “other” fuel category to convert energy units to mass units. Taken as a whole, the estimate of energy recovery emissions probably introduces more uncertainty than any other element of the non-energy analysis.

### ***Plastics***

Uncertainty in the carbon storage estimate for plastics arises primarily from three factors. First, the production data for acrylonitrile-butadiene-styrene, styrene-acrylonitrile, polyvinyl chloride, polypropylene, phenolic, urea, melamine, and thermoplastic polyester resins include Canadian production and may overestimate the amount of plastic produced from U.S. fuel feedstocks. Second, the assumed carbon content values are estimates for representative compounds, and thus do not account for the many formulations of resins available. This uncertainty is greater for resin categories that are generic (e.g., phenolics, other styrenics, nylon) than for resins with more specific formulations (e.g., polypropylene, polyethylene). Lastly, the assumption that all of the carbon contained in plastics is stored ignores certain end uses (e.g., adhesives and coatings) where the resin may be released to the atmosphere; however, these end uses are likely to be small relative to use in plastics.

### ***Rubber***

Similar to plastics, uncertainty results from using consumption data for the United States and Canada, rather than just domestic consumption, which may overestimate the amount of rubber produced from U.S. fuel feedstocks. There are also uncertainties as to the assignment of carbon content values; however, they are much smaller than in the case of plastics. There are probably fewer variations in rubber formulations than in plastics, and the range of potential carbon content values is much narrower. Lastly, assuming that all of the carbon contained in rubber is stored ignores the possibility of volatilization or degradation during product lifetimes. However, the proportion of the total carbon that is released to the atmosphere during use is probably negligible.

### ***Fibers***

A small degree of uncertainty arises from the assignment of carbon content values; however, the magnitude of this uncertainty is less than that for plastics or rubber. Although there is considerable variation in final textile products, the stock fiber formulations are standardized and proscribed explicitly by the Federal Trade Commission.

### ***Pesticides***

The largest source of uncertainty involves the assumption that a pesticide’s active ingredient carbon is either 0 percent stored or 100 percent stored. This split is a generalization of chemical behavior, based upon active-

ingredient molecular structure, and not on compound-specific environmental data. The mechanism by which a compound is bound or released from soils is very complicated and can be affected by many variables, including the type of crop, temperature, delivery method, and harvesting practice. Another smaller source of uncertainty arises from the carbon content values applied to the unaccounted for portion of active ingredient. Carbon contents vary widely among pesticides, from 7 to 72 percent, and the remaining pesticides may have a chemical make-up that is very different from the 32 pesticides that have been examined.

## Asphalt and Road Oil

Asphalt is one of the principal non-energy uses of fossil fuels. The term “asphalt” generally refers to a mixture of asphalt cement and a rock material aggregate, a volatile petroleum distillate, or water. For the purposes of this analysis, “asphalt” is used interchangeably with asphalt cement, a residue of crude oil. According to EIA (2000d), approximately 100 Tg CO<sub>2</sub> Eq. has been used in the production of asphalt cement annually. Though minor amounts of carbon are emitted during production, asphalt has an overall carbon storage factor of almost 100 percent.

Paving is the primary application of asphalt cement, comprising 86 percent of production. The three types of asphalt paving produced in the United States are hot mix asphalt (HMA), cut-backs, and emulsified asphalt. HMA, which makes up 90 percent of total asphalt paving (EPA 2000d), contains asphalt cement mixed with an aggregate of rock materials. Cut-back asphalt is composed of asphalt cement thinned with a volatile petroleum distillate (e.g., naphtha). Emulsified asphalt contains only asphalt cement and water. Roofing products are the other significant end use of asphalt cement, accounting for approximately 14 percent of U.S. production (Kelly 2000). No data were available on the fate of carbon in asphalt roofing; it was assumed that it has the same fate as carbon in asphalt paving applications.

### Methodology

A carbon storage factor was calculated for each type of asphalt paving. The fraction of carbon emitted by each asphalt type was multiplied by consumption data for asphalt paving (EPA 2000d, EIIP 1998) to come up with a weighted average carbon storage factor for asphalt as a whole.

The fraction of carbon emitted by HMA was determined by first calculating the organic emissions (volatile organic compounds [VOCs], carbon monoxide, polycyclic aromatic hydrocarbons [PAHs], hazardous air pollutants [HAPs], and phenol) from HMA paving, using emission factors reported in EPA (2000d) and total HMA production.<sup>9</sup> The next step was to estimate the carbon content of the organic emissions. This calculation was based on stoichiometry for carbon monoxide (CO) and phenol, and an assumption of 85 percent carbon content for PAHs and HAPs. The carbon content of asphalt paving is a function of the proportion of asphalt cement in asphalt paving and the proportion of carbon in asphalt cement. For the former factor, a 5 percent asphalt cement content was assumed based on personal communication with an expert from the National Asphalt Paving Association (Connolly 2000). For the latter factor, all paving types were characterized as having a mass fraction of 85 percent carbon in asphalt cement, based on the assumption that asphalt is primarily composed of saturated paraffinic hydrocarbons. By combining these estimates, the result is that over 99.99 percent of the carbon in asphalt cement was retained (i.e., stored), and less than 0.01 percent was emitted.

Cut-back asphalt is produced in three forms (i.e., rapid, medium and slow cure). All three forms emit carbon only from the volatile petroleum distillate used to thin the asphalt cement (EPA 1995). Because the petroleum distillates are not included in the EIA statistics for asphalt, the storage factor for cut-back is assumed to be 100 percent.

It was also assumed that there was no loss of carbon from emulsified asphalt (i.e., the storage factor is 100 percent) based on personal communication with an expert from Akzo Nobel Coatings, Inc. (James 2000).

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<sup>9</sup> The emission factors are expressed as a function of asphalt paving tonnage (i.e., including the rock aggregate as well as the asphalt cement).

## Data Sources

Data on asphalt and road oil consumption and carbon content factors were supplied by EIA. Hot mix asphalt production and emissions factors were obtained from “Hot Mix Asphalt Plants Emissions Assessment Report” from EPA’s *AP-42* (EPA 2000d) publication. The asphalt cement content of HMA was provided by Una Connolly of National Asphalt Paving Association (Connolly 2000). The consumption data for cut-back and emulsified asphalts were taken from a Moulthrop, et al. study used as guidance for estimating air pollutant emissions from paving processes (EIIP 1998). “Asphalt Paving Operation” *AP-42* (EPA 1995) provided the emissions source information used in the calculation of the carbon storage factor for cut-back asphalt. The storage factor for emulsified asphalt was provided by Alan James of Akzo Nobel Coatings, Inc. (James 2000).

## Uncertainty

The principal source of uncertainty is that the available data are from short-term studies of emissions associated with the production and application of asphalt. As a practical matter, the cement in asphalt deteriorates over time, contributing to the need for periodic re-paving. Whether this deterioration is due to physical erosion of the cement and continued storage of carbon in a refractory form or physicochemical degradation and eventual release of CO<sub>2</sub> is uncertain. Long-term studies may reveal higher lifetime emissions rates associated with degradation.

Many of the values used in the analysis are also uncertain and are based on estimates and professional judgment. For example, the asphalt cement input for HMA was based on expert advice indicating that the range is variable—from about 3 to 5 percent—with actual content based on climate and geographical factors (Connolly 2000). Over this range, the effect on the calculated carbon storage factor is minimal (on the order of 0.1 percent). Similarly, changes in the assumed carbon content of asphalt cement would have only a minor effect.

The consumption figures for cut-back and emulsified asphalts are based on information reported for 1994. More recent trends indicate a decrease in cut-back use due to high VOC emission levels and a related increase in emulsified asphalt use as a substitute. However, because the carbon storage factor of each is 100 percent, use of more recent data would not affect the overall result.

## Lubricants

Lubricants are used in industrial and transportation applications. They can be subdivided into oils and greases, which differ in terms of physical characteristics (e.g., viscosity), commercial applications, and environmental fate. According to EIA (2000), the carbon content of U.S. production of lubricants in 1999 was approximately 28 Tg CO<sub>2</sub> Eq. Based on apportioning oils and greases to various environmental fates, and characterizing those fates as resulting in either long-term storage or emissions, the overall carbon storage factor was estimated to be 9 percent; thus, storage in 1999 was about 3 Tg CO<sub>2</sub> Eq.

## Methodology

For each lubricant category, a storage factor was derived by identifying disposal fates and applying assumptions as to the disposition of the carbon for each practice. An overall lubricant carbon storage factor was calculated by taking a production-weighted average of the oil and grease storage factors.

## Oils

Regulation of used oil in the United States has changed dramatically over the past 15 years.<sup>10</sup> The effect of these regulations and policies has been to restrict land filling and dumping, and to encourage collection of used oil. Given the relatively inexpensive price of crude oil, the economics have not favored re-refining—instead, most of the used oil that has been collected has been combusted.

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<sup>10</sup> For example, the U.S. EPA “RCRA (Resource Conservation and Recovery Act) On-line” web site (<http://www.epa.gov/rcraonline/>) has over 50 entries on used oil regulation and policy for 1994 through 2000.



Table C-15 provides an estimated allocation of the fates of lubricant oils, along with an estimate of the proportion of carbon stored in each fate. The ultimate fate of the majority of oils (about 84 percent) is combustion, either during initial use or after collection as used oil. Combustion results in 99 percent oxidation to CO<sub>2</sub>, with correspondingly little long-term storage of carbon in the form of ash. Dumping onto the ground or into storm sewers, primarily by “do-it-yourselfers” who change their own oil, is another fate that results in conversion to CO<sub>2</sub> given that the releases are generally small and most of the oil is biodegraded. In the landfill environment, which tends to be anaerobic, within municipal landfills, it is assumed that 90 percent of the oil persists in an undegraded form. Re-refining adds a recycling loop to the fate of oil; it was assumed that about 97 percent of the carbon in re-refined oil is ultimately oxidized. Because of the dominance of fates that result in eventual release as CO<sub>2</sub>, only about 3 percent of the carbon in oil lubricants goes into long-term storage.

**Table C-15: Commercial and Environmental Fate of Oil Lubricants (Percent)**

Fate of Oil	Portion of Total	
	Oil	Carbon Stored
<b>Combusted During Use</b>	<b>20</b>	<b>1</b>
<b>Not Combusted During Use</b>	<b>80</b>	<b>-</b>
Combusted as Used Oil*	64	1
Dumped on the ground or in storm sewers	6	0
Landfilled	2	90
Re-refined into lube oil base stock and other products	8	3
<b>Weighted Average</b>	<b>-</b>	<b>2.9</b>

\* (e.g., in boilers or space heaters)

- Not applicable

### Greases

Table C-16 provides analogous estimates for lubricant greases. Unlike oils, grease is generally not combusted during use, and combustion for energy recovery and re-refining are thought to be negligible. Although little is known about the fate of waste grease, it was assumed that 90 percent of the non-combusted portion is landfilled, and the remainder is dumped onto the ground or storm sewers. Because much of the waste grease will be in containers that render it relatively inaccessible to biodegradation, it was assumed that 90 percent and 50 percent of the carbon in landfilled and dumped grease, respectively, would be stored. The overall storage factor is 82 percent for grease.

**Table C-16: Commercial and Environmental Fate of Grease Lubricants (Percent)**

Fate of Grease	Total Grease	Carbon Stored
<b>Combusted During Use</b>	<b>5</b>	<b>1</b>
<b>Not Combusted During Use</b>	<b>95</b>	<b>-</b>
Landfilled	85.5	90
Dumped on the ground or in storm sewers	9.5	50
<b>Weighted Average</b>	<b>-</b>	<b>81.8</b>

- Not applicable

Having derived separate storage factors for oil and grease, the last step was to estimate the weighted average for lubricants as a whole. No data were found apportioning the mass of lubricants into these two categories, but the U.S. Census Bureau does maintain records of the value of production of lubricating oils and lubricating greases. Assuming that the mass of lubricants can be allocated according to the proportion of value of production (92 percent oil, 8 percent grease), applying these weights to the storage factors for oils and greases (3 percent and 82 percent) yields an overall storage factor of 9 percent.

### Data Sources

The estimated volume of lubricants produced annually is based on statistics provided by EIA (2000), which conducts surveys of lubricating oil and grease consumption. Information on the value of lubricating oil and grease production was obtained from reports by the U.S. Census Bureau (1999).

The characterization of fate is based primarily on professional judgment of an EPA regulatory analyst with experience in used oil (Rinehart 2000). For the proportions combusted, one percent was assumed to remain un-

oxidized in combustion processes (EIIP 1999); for other fates, estimates are based on professional judgment. The assumption that landfilled oil and grease results in 90 percent storage is based on analogy with the persistence of petroleum in native petroleum-bearing strata, which are both anaerobic. The assumption that oil dumped on the ground or in storm sewers is completely degraded is based on the observation that land farming—application to soil—is one of the most frequently used methods for degrading refinery wastes. The lower degradation rate for grease is based on the observation that greases contain longer chain paraffins, which are more persistent. Re-refined oil was assumed to have a storage factor equal to the weighted average for the other fates (i.e., after re-refining, the oil would have the same probability of combustion, landfilling, or dumping as virgin oil).

### **Uncertainty**

The principal sources of uncertainty for the disposition of lubricants are the estimates of the commercial use, post-use, and environmental fate of lubricants, which, as noted above, are largely based on assumptions and judgment. There is no comprehensive system to track used oil and greases, which makes it difficult to develop a verifiable estimate of the commercial fates of oil and grease. The environmental fate estimates for percent of carbon stored are less uncertain, but also introduce uncertainty in the estimate.

The assumption that the mass of oil and grease can be divided according to their value also introduces uncertainty. Given the large difference between the storage factors for oil and grease, changes in their share of total lubricant production have a large effect on the weighted storage factor.